Advanced Underwater Imaging Phase III Annual Report FY07

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LONG-TERM GOALS

The overall objective of the Advanced Underwater Imaging (AUI) program is to advance the state of the art in wide-swath underwater laser imaging with the long-term goal of transitioning this technology to the Navy's fleet of 21" diameter and smaller form factor autonomous underwater vehicles (AUVs).

OBJECTIVES

The objectives of the work performed during this funding period were to:

1. Gain an understanding of the limitations of the simulation results obtained with the pulsed laser line scan (PLLS) time history and image simulation software, by comparing simulation results with measured data.

2. Gain an understanding of the technological and system performance trade-offs in the design of a wide-swath extended range underwater optical imager (ERUWOI) which is suitable to be deployed from the common form factor AUV.

3. Analyze the performance of candidate autonomous image quality optimization computer algorithms using measured data to provide a metric for comparison of the PLLS and LLS imaging methods.

4. Investigate the potential to achieve increased system range and image contrast via the use of high frequency pulse modulation and coding techniques.

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APPROACH

The approach for meeting these objectives within this funding period involved continuing collaborations with Physical Sciences Inc (Andover, MA) and Metron Inc (Reston, VA) in the areas of image analysis and radiative transfer modeling. In summary the proposed technical approach consisted of the following activities:

1. Make improvements to previously developed Metron PLLS simulation software and perform experimental code validation tests with a high power green pulsed laser in the HBOI extended range underwater test facility.

2. Development and testing of a benchtop prototype PLLS underwater imaging architecture using a custom-made high power, high repetition rate green laser.

3. Design an experimental plan and acquire images using developed hardware for evaluation of image quality optimization algorithms used for comparison and evaluation of PLLS and LLS system approaches.

4. Using the Metron time history code and an additional signal processing layer developed using Matlab, perform modeling and simulation of high frequency pulse modulation and coding techniques which may have the potential for improving system performance.

WORK COMPLETED

1. Imager performance prediction and time history simulation code (version 2)

During the last year, the pulse time history code has been continually improved and updated. The most notable changes to the code have been:

i. increasing the allowable time resolution to enable modeling of shorter pulses, as needed for a modulated and pulsed LLS system modeling comparison

ii. adding capability to model the increased attenuation and spherical spreading associated with off-nadir (slant range) imaging

iii. the introduction of a user defined scattering phase function

iv. the ability for the user to specify the time resolution

v. refinements to the solar ambient background contribution to the noise

vi. modeling of intentional misalignment of the source and receiver axes by the user.

The code has been system tested with a defined test matrix and known bugs have been corrected. Several sets of time history analytical versus experimental comparisons have been made in this funding period and are currently under analysis.

2. Experimental work with prototype PLLS hardware

Throughout the period of funding, necessary experimental activities were performed to test and characterize the various custom-fabricated or 'off-the-shelf' modules and devices comprising the PLLS system. The most recent activities involved in-water system acceptance testing of the benchtop PLLS imaging system, using a high power, high repetition rate green pulsed laser. Initial images from the system are presented in the 'results' section.

3. Image quality optimization study

An approach to image quality optimization that involves intentionally varying settings within the imager itself to improve images that may be slightly 'out of focus' was investigated. The algorithm was implemented in Matlab and results were produced and analyzed using LLS images obtained from an existing "at-sea" database, and in a highly controlled tank environment using the HBOI LLS benchtop prototype imaging system

4. Simulation of coded pulse detection in turbid water

Utilizing the latest Metron code with finer time resolution, it has been possible to investigate the benefits of several alternative pulse modulation and coded pulse schemes. Such techniques show potential to make additional improvement in achievable signal-to-noise ratio and timing resolution (and may also make possible a reduction in the limiting forward scattered light) by careful selection of the modulated code using a coherent detection method at the system back end.

RESULTS

1. Simulation results with new Metron code

The latest version of the Metron PLLS code was exercised in the highly scattering environment in which the PLLS is expected to have improved performance to the CW LLS imager. Figure 1 shows a typical time history result.

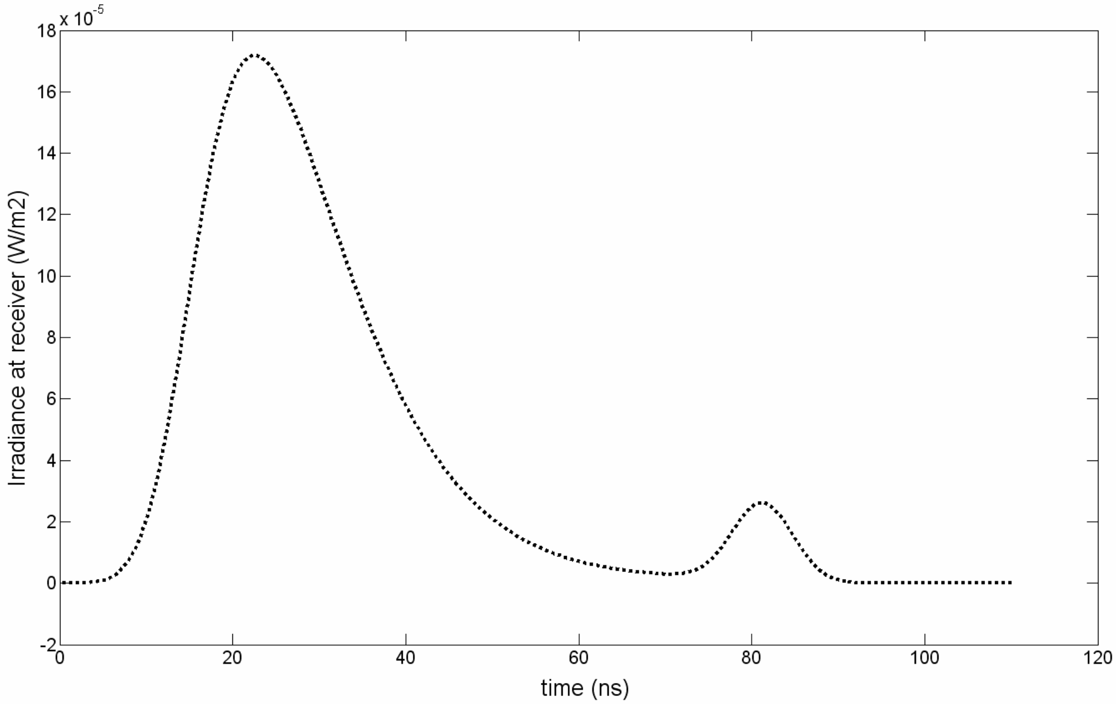

Figure 1: Temporal return at receiver for highly scattering coastal waters (b=0.9m^{-1}, c=1.0m^{-1}) at 9 attenuation lengths (9 meters). [Laser pulse FWHM = 7ns. Average power at 350KHz = 2.5W. Source-receiver separation = 0.1m. Angular aperture = 15mrad. Target reflectance = 0.1. McLean-Freeman phase function is used.]

It can be seen that the target return signal (centered at t=80ns) would likely be separable from the large backscattering signal if a suitable gating scheme is chosen. When the same input parameters are used in the CW LLS image simulation code, no discernable image is produced.

The Metron image simulation software was also used to examine the system parameter trade-offs for a PLLS imager close to its limiting case. Figure 2 shows the effect of variations in laser pulse width and average laser power at 8 attenuation lengths, also with a comparison to CW LLS performance at various source-receiver separations. A major benefit we have seen in these results, is that the use of pulses allows the imager to be configured to be more compact without a major impact to the imaging performance. Assuming a suitable gating scheme can be employed, increasing the average laser power will continue to improve the performance of the PLLS imager.

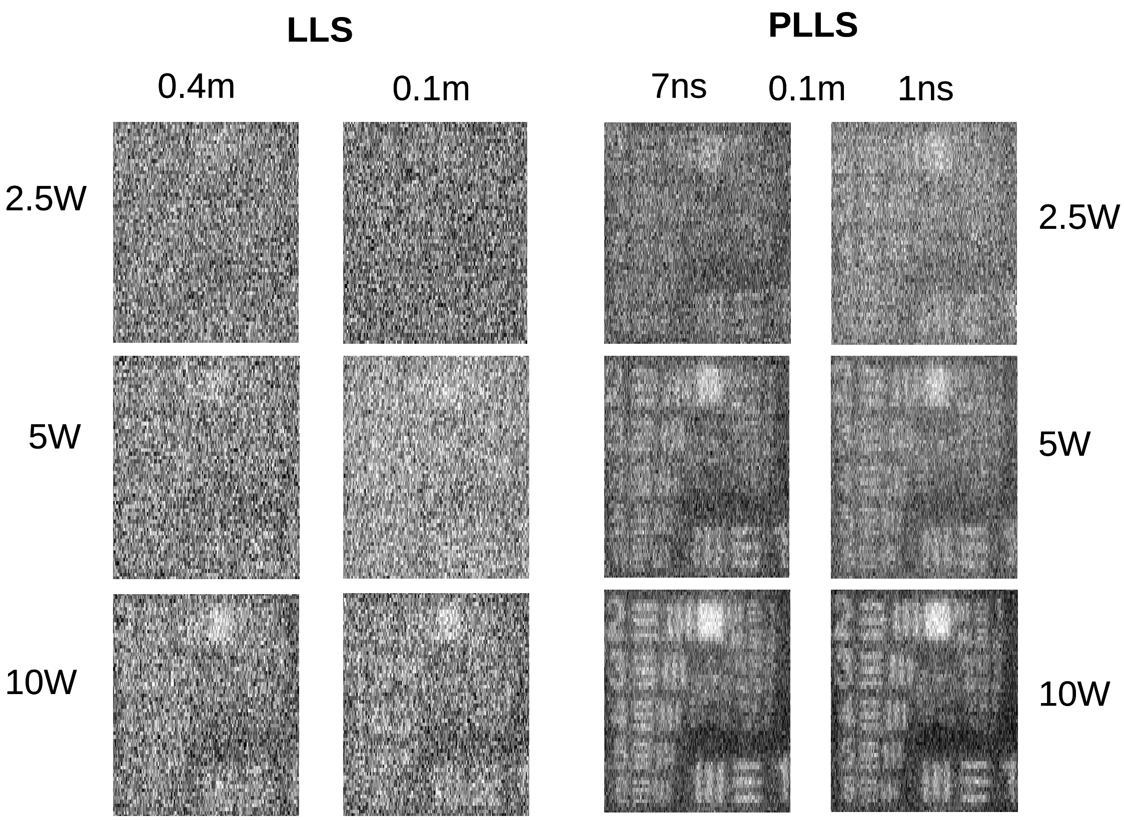

Figure 2: Simulated images in highly scattering shallow coastal waters at 8 Attenuation lengths. [LLS images use source-receiver separation of 0.4m and 0.1m, PLLS images use 0.1m separation with 7ns and 1ns FWHM pulses. Average power for all cases is noted at the side. $b=1.0m^{-1}$, $c=1.6m^{-1}$, stand-off distance=5m, reflectance of black is 0.05, white is 0.15, angular aperture=25mrad. Note that the PLLS system shows an apparent improvement in image contrast over the CW LLS at equivalent average power level.]

These simulated images and time history results are based on the computation of backscatter and target temporal return photons arriving at the entrance to the receiver from laser and ambient sources, and therefore do not consider practical limitations of available pulsed and cw sources, as well as the various noise contributions inherent to suitable receiver configurations. The extent to which these limitations affect performance is being established via ongoing experimentation and modeling.

2. Experimental results

Figure 3 shows a time history plot taken at 6.3 attenuation lengths over 9 meters target distance with a 50% reflectance target in a test tank. These results suggest that the PLLS would be easily capable of acquiring images in these conditions.

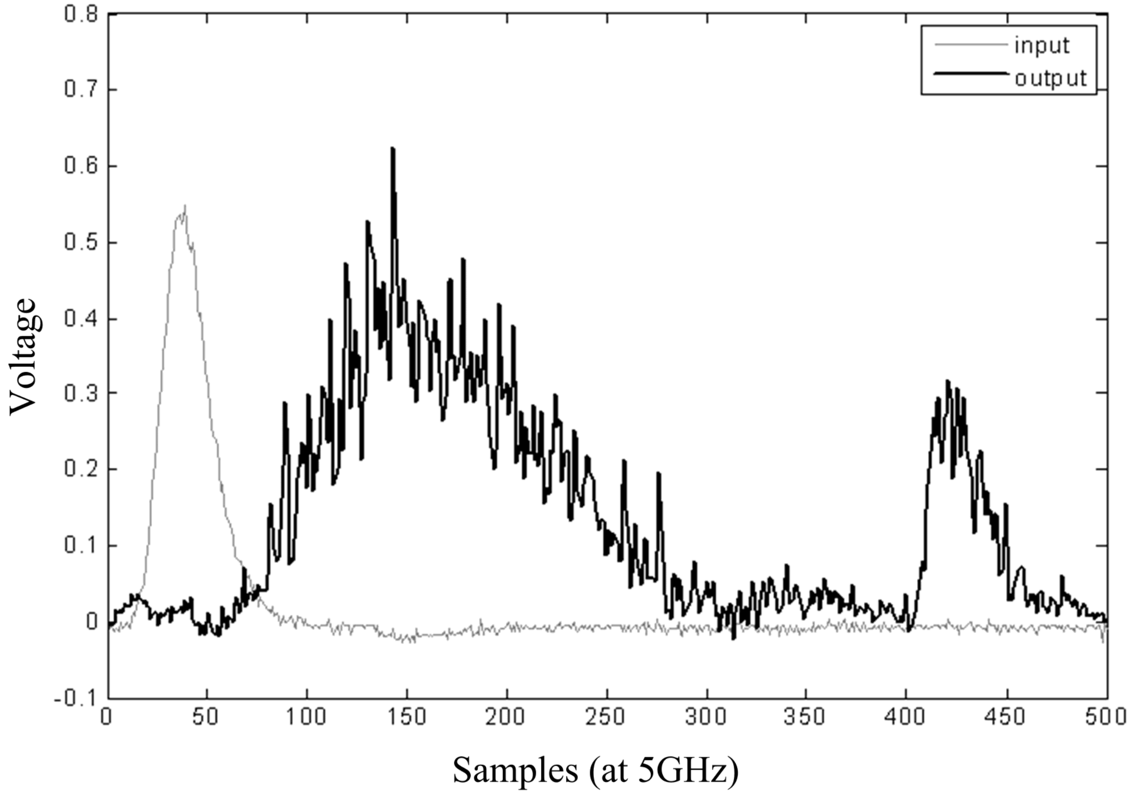

Figure 3: Temporal return measured in test tank with a gated MCP-PMT for Maalox-dosed fresh water (b=0.56m^{-1}, c=0.7m^{-1}) at 6.3 Attenuation lengths (9 meters). [Source-receiver separation = 0.25m. Angular aperture = 25mrad. Note the input pulse was measured with a 2GHz Si detector and is shown in gray. The MCP-PMT gate was opened 50ns prior to the input pulse being transmitted into the test tank.]

A PLLS benchtop imager demonstrator was also designed and fabricated within this funding period, and initial results from the benchtop hardware have been obtained.

Initial raw images from the system compared with those from the Metron image simulation software are shown in figures 4-6. It should be noted that due to hardware problems, the system was operated without a PMT amplifier for the results displayed, --significantly reducing image bit depth, which is particularly noticable in figure 6. In addition, noise from a faulty PMT power supply, and from laser pulse instability was present in thse images, further reducing image quality.

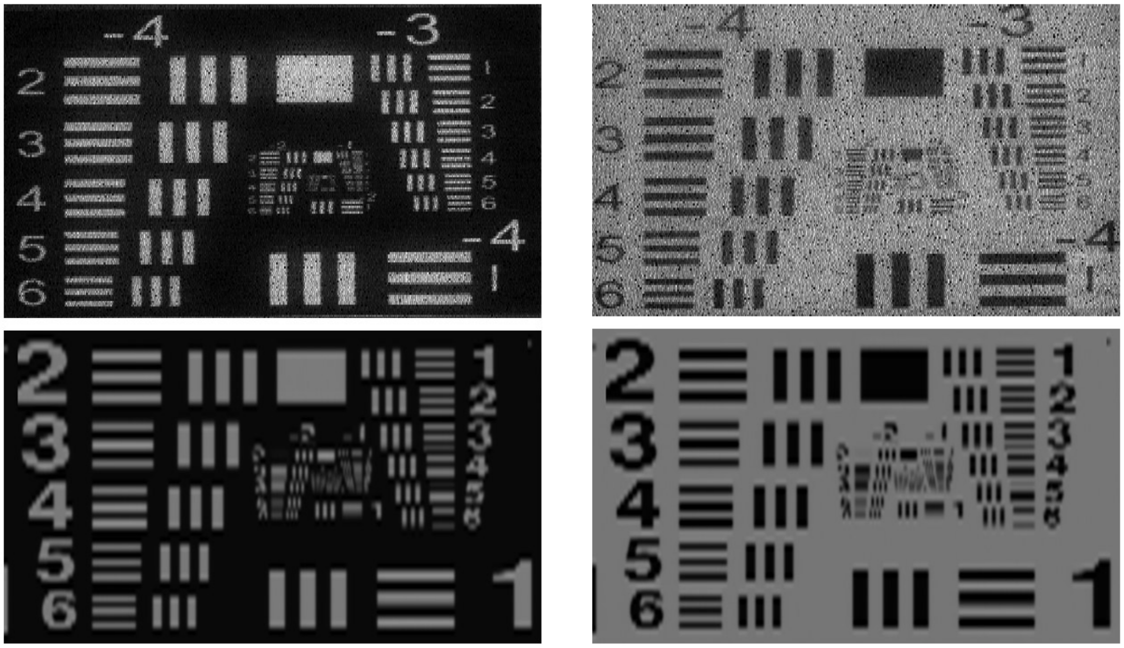

Figure 4: Raw images (top) and simulated images (bottom) of USAF technical targets at 1.3 attenuation lengths. [Polygon speed = 1000rpm, stand-off distance = 3m, b=0.29m^{-1}, c=0.43m^{-1}]

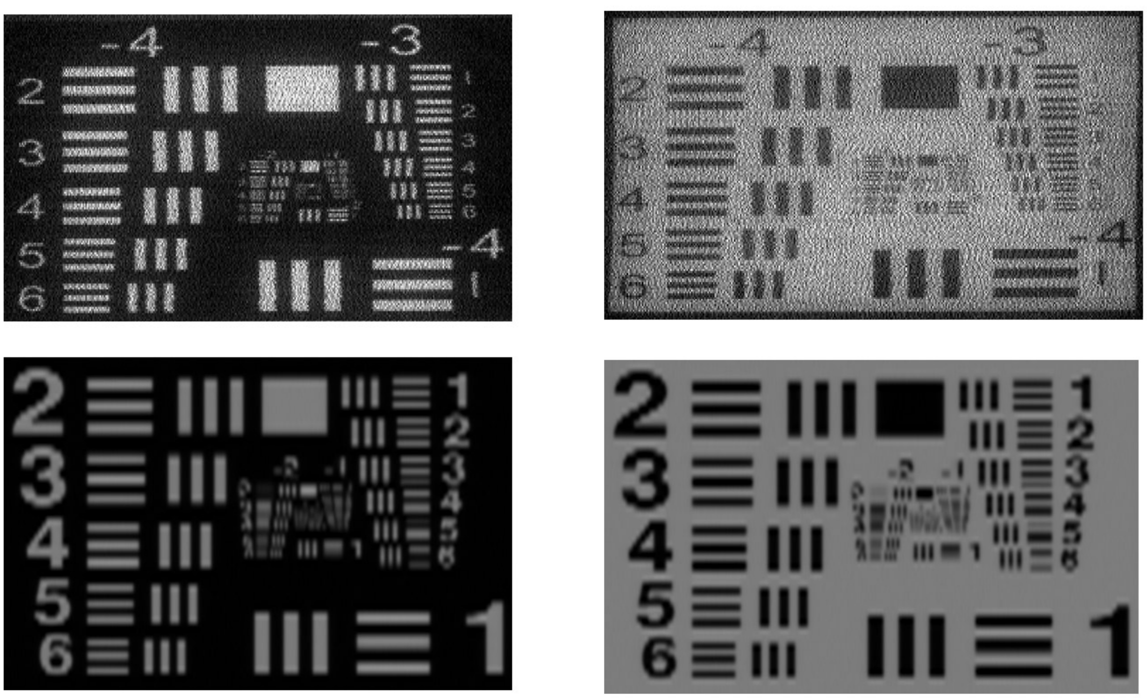

Figure 5: Raw images (top) and simulated images (bottom) of USAF technical targets at 2.2 attenuation lengths. [Polygon speed = 1000rpm, stand-off distance = 5m, b=0.29m^{-1}, c=0.43m^{-1}]

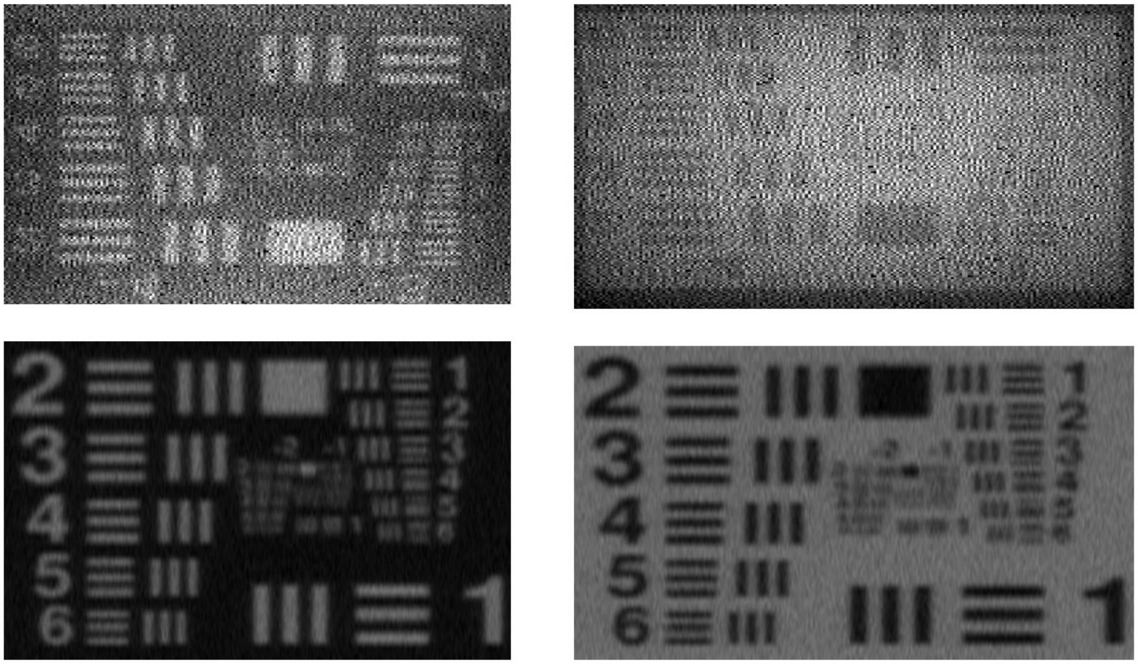

Figure 6: Raw images (top) and simulated images (bottom) of USAF technical targets at 4.3 attenuation lengths. [Polygon speed = 1000rpm, stand-off distance = 10m, b=0.29m^{-1}, c=0.43m^{-1}]

Although noise sources currently limit the performance of the system to approximately 5 attenuation lengths, simulations using the custom developed Metron code indicate that the PLLS imager can produce images at 8-9 attenuation lengths. The LLS system under similar conditions, however, shows no discernable image. The noise level of the receiver assembly is a current issue but can be reduced with the expectation of producing images at greater stand-off distances than the LLS approach. Ongoing work will also utilize pulse energy normalization on a pulse-to-pulse basis to reduce image impulse noise from its current 2:1 value. Other efforts will concentrate on suppressing the receiver gating noise.

3. Simulation of coded pulse coherent detection in turbid water

A laser pulse linear frequency chirp (with equivalent energy to the longer laser pulses used in the PLLS work) was used as an input to the Metron time history code. This coded pulse together with the computed time history response is shown in figure 7. Although the target return pulse train (between t = 54ns to 69ns in the time history response plot) is extremely weak at 9 attenuation lengths, the calculated peak signal irradiance is within the detection threshold of the fast MCP-PMT device being used with the PLLS.

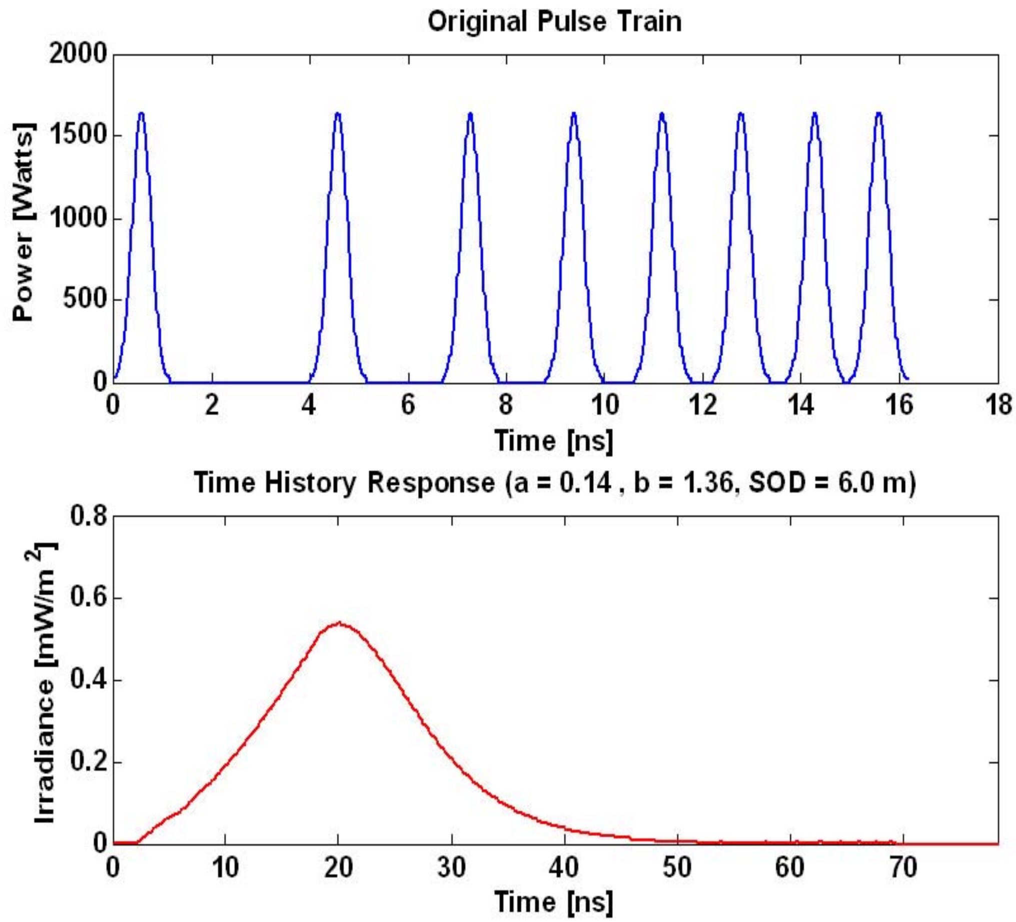

Figure 7: Laser pulse chirp sequence input (top) and time history response (bottom) for 9 attenuation lengths at 6 meters stand-off distance. [a weak target return pulse train at t = 54ns – 69ns is nearly imperceptible on the lower plot]

Figure 8 shows that detection of the original signal is possible with a high speed gated receiver and enhanced with a cross-correlation processing stage. The detection benefits and resulting imager performance improvements with several candidate coded-pulse waveforms when compared to the single pulse PLLS is ongoing research and this work will also leverage the gated-PMT modeling effort which is to be performed in the current year.

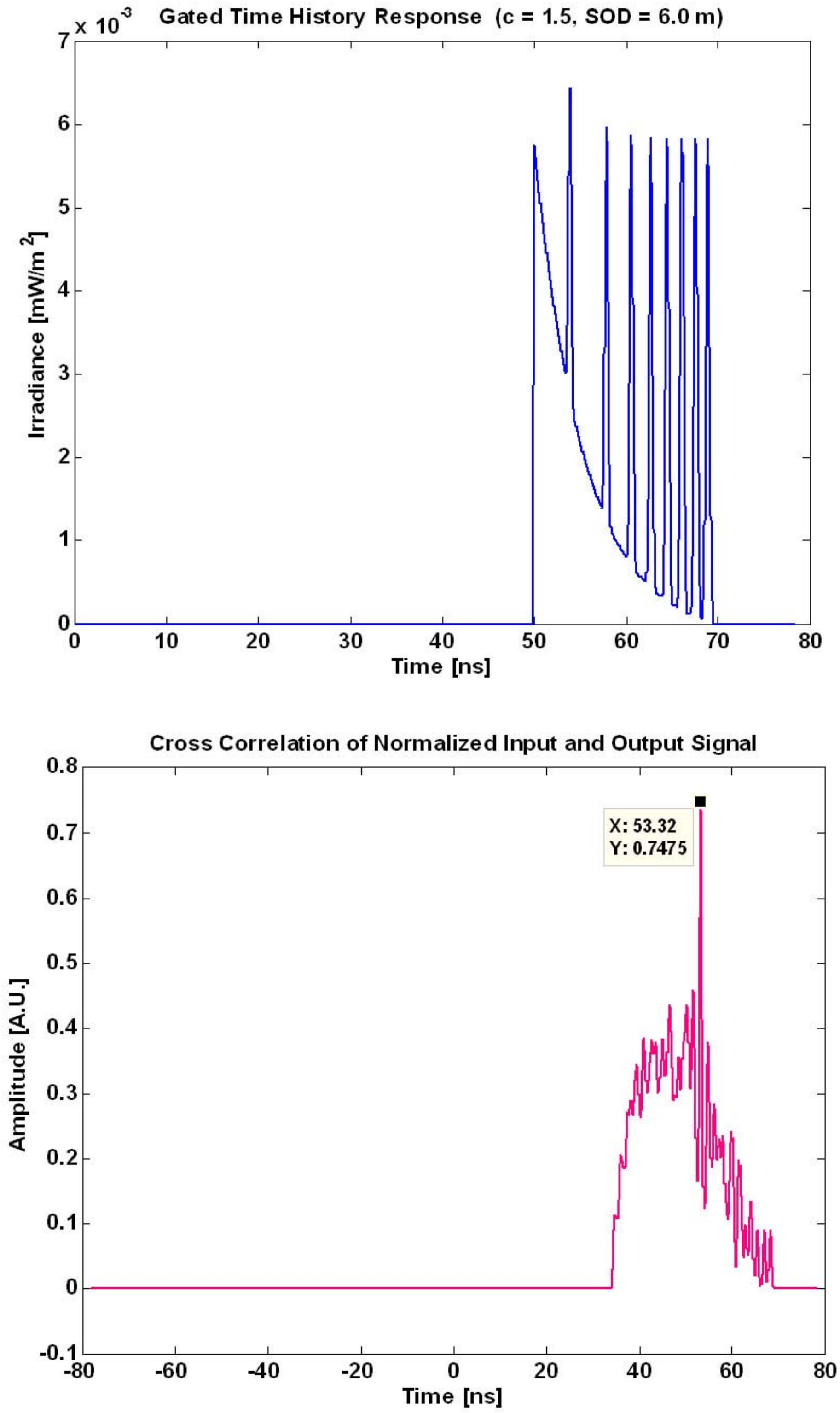

Figure 8: Simulated laser pulse chirp gated return signal (top) and cross-correlation results (bottom) at 9 attenuation lengths.

IMPACT/APPLICATIONS

The PLLS system has shown both analytically and experimentally to be capable of extending the operational range of wide-swath optical imaging systems in turbid water beyond the current state-of-the-art of 5 to 6 attenuation lengths. For example, simulation results suggest that the limits of operability of the PLLS to be up to 9 attenuation lengths in turbid coastal conditions. Although the practical performance will likely be less than this, some tests with the current detection hardware suggest performance beyond 6 attenuation lengths is already possible. The PLLS does not require a significant source-receiver separation to produce quality images, and hence allows for more compact, simpler optical designs which have the potential to be more immune to changes in operating conditions, and hence more reliable than the current state-of-the-art.

The transitioning of such a system into the Navy's fleet of AUVs would certainly be beneficial in the context of MCM and ISR missions. However the PLLS not only has benefits in identifying targets of potential military or homeland security interest, but may also be a valuable tool for the AUV survey community, either within the offshore hydrocarbon and telecommunications industries for seabed inspection purposes, or for scientific exploration and environmental monitoring applications.

RELATED PROJECTS

A set of experiments have been planned for the week of 22nd October 2007 with Linda Mullen's group at NAVAIR. The objectives are to evaluate the performance of the CW modulated LLS FAMIS system when used with a synchronous scanning architecture, and to compare the imaging performance in turbid water conditions with that of the PLLS. Comparisons with the image prediction models for both systems will be performed and reported.

PUBLICATIONS

Dalgleish, F.R., Caimi, F.M., Britton, W.B. and Andren, C.F., "An AUV-deployable pulsed laser line scan (PLLS) imaging sensor" *Oceans 2007, October 2-5, Vancouver, Canada.*

Caimi, F.M., Dalgleish, F.R., Giddings, T.E. Shirron, J.J., Mazel, C.H., Chiang, K. "Pulse versus CW laser line scan imaging detection methods: simulation results" *Oceans Europe 2007, June 18-21, 2007,* Aberdeen, Scotland.

Dalgleish, F.R., Caimi, F.M., Mazel, C.H., Glynn, J.M., Chiang, K., Giddings, T.E. and Shirron, J.J. "Model-based evaluation of pulsed lasers for an underwater laser line scan imager". *Ocean Optics XVIII. October 9-11, 2006, Montreal, Canada.*

Dalgleish, F.R., Bordner, P.R and Caimi, F.M. "HBOI extended range optical imaging test facility". *Ocean Optics XVIII. October 9-11, 2006, Montreal, Canada.*

Dalgleish, F.R., Caimi, F.M., Mazel, C.H. and Glynn, J.M. "Extended Range Underwater Optical Imaging Architecture". *MTS/IEEE Oceans 2006, September 18-21 2006, Boston, MA.*

PATENTS

METHOD AND APPARATUS FOR SYNCHRONOUS LASER BEAM SCANNING
U.S. Patent Application No. 11/857,039 (Pending)